Full vector inversion of magnetic microscopy images using Euler deconvolution as a priori information

Gelson Ferreira de Souza Junior[1*], Leonardo Uieda[2], Ricardo Ivan Ferreira da Trindade[1], Janine Carmo[1], and Roger Fu[3]

[1]Universidade de São Paulo, Brazil
[2]University of Liverpool, UK
[3]Harvard University, USA
[*]Corresponding author: EMAIL@MEH.BLA

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Abstract

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1 Introduction

Several branches of Earth Sciences have demonstrated the importance of the "spatiality" of the data on a microscopic scale, mainly in geochemistry and geochronology applications where it is possible to perform punctual analysis and compositional maps, allowing significant advances in the understanding of igneous, metamorphic and sedimentary processes (Barnes et al., 2019; Davidson et al., 2007; Verberne et al., 2020). Classical paleomagnetic techniques, on the other hand, consist in analyzing bulk samples, where the magnetic signal of a single specimen is the result of the sum of moments of a large assembly of ferromagnetic grains (Dunlop and Özdemir, 1997). Typically, a standard paleomagnetic sample of ~10 cm³ would contain hundreds of thousands to millions of magnetic particles with sizes varying from magnetically stable single-domain (SD) and vortex state grains (also called pseudo-single domain, PSD) with sizes below 1 µm, to large ($\gg$ 1 µm) grains with multi-domain (MD) magnetic structures, which are less stable magnetic recorders (Berndt et al., 2016). These large MD grains usually conceal the signal of the SD and PSD grains, and techniques of step-wise thermal and magnetic treatments are needed to unveil the more stable and reliable magnetic record (Tauxe et al., 2018). Recently, magnetic microscopy techniques opened the possibility of performing magnetic maps at the micro-scale and recovering the magnetization of each grain, therefore enabling the separate analysis of stable and unstable magnetic particles (de Groot et al., 2014, 2018; Lima et al., 2014; Weiss et al., 2007).

In order to apply magnetic microscopy to paleomagnetic studies, it is necessary to recover from the magnetic images a large amount of individual magnetic moments, corresponding to at least tens of thousands of stable fine-grained grains (<1 µm), in order to provide statistical significance to the remanence vector (e.g. Berndt et al., 2016). Nowadays, with the development of magnetic microscopy techniques, this task is no longer limited by the resolution of magnetic microscopes (de Groot et al., 2018; Fu et al., 2020; Glenn et al., 2017; Lima et al., 2014; Weiss et al., 2007), but essentially by the intrinsic problem presented by the ambiguity in the inversion of potential field data (Barbosa and Silva, 2011; de Groot et al., 2021; Oliveira Jr. et al., 2015), and ultimately by the lack of a fast and automated way to recover such a large number of individual magnetic moments from a set of magnetic images (CortésOrtuño et al., 2022; Lima and Weiss, 2009; Lima et al., 2013). A solution to the non-uniqueness of magnetic moment inversion is to add independent a priori information, such as the position of the ferromagnetic particles (Fabian and Groot, 2019). This can be obtained, for example, from X-ray computed tomography (microCT; de Groot et al., 2021, 2018; Fabian and Groot, 2019). Nonetheless, the standard microCT techniques do not provide adequate resolution to resolve the finer and more stable magnetic grains (CortésOrtuño et al., 2022; de Groot et al., 2021), whereas other more sophisticated techniques such as ptychographic X-ray tomography (e.g., Maldanis et al., 2020) are not readily available and too time-consuming to be routinely used in paleomagnetic studies.

Another route to be explored in the inversion of magnetic microscopy images is to obtain all the information, i.e. the magnetic moment and the position of the sources, from the magnetic data itself (e.g., Fu et al., 2020). For that, we can explore the techniques developed

	Position			Dipole moment		
	x_c (μm)	y_c (μm)	z_c (μm)	I (°)	D (°)	m (A.m²)
true	800.00	200.00	-3.50	22.00	125.00	5.000e-15
estimated	800.00	199.91	-3.43	21.59 ± 0.01	125.01 ± 0.02	4.943e-15 ± 1.3e-18
true	750.00	750.00	-8.50	62.00	10.00	1.500e-14
estimated	750.02	750.01	-8.41	62.04 ± 0.01	10.40 ± 0.02	1.484e-14 ± 1.9e-18
true	250.00	250.00	-10.00	-30.00	-140.00	1.000e-14
estimated	249.99	250.08	-9.80	-29.93 ± 0.01	-140.65 ± 0.02	9.785e-15 ± 2.7e-18
true	500.00	500.00	-7.75	-50.00	-70.00	2.000e-15
estimated	499.46	500.20	-7.46	-55.53 ± 0.07	-68.92 ± 0.14	1.821e-15 ± 2.0e-18

Table 1: Meh

in exploration geophysics, in spite of the differences between aeromagnetic surveys and magnetic microscopy (Lima et al., 2013). Magnetic microscopy images commonly show the combined signal of multiple magnetic particles and can vary greatly in wavelength, strength, and spatial separation, depending on the NRM and location of each particle. We usually assume that the signal measured by the magnetic microscope is the vertical component of the magnetic induction vector (b_z), the measurements are performed on a regular grid with evenly spaced grid points and at a constant height, and the data are contaminated with random Gaussian noise and long-wavelength noise (akin to a regional signal in aeromagnetic data). Here, we provide a methodological routine to retrieve the individual magnetic moment of ferromagnetic grains in magnetic microscopy images following the approach devised by Oliveira Jr. et al. (2015) for the interpretation of aeromagnetic anomalies. The method we propose allows one to quickly and semi-automatically estimate the individual magnetic moment vector of the stable magnetic carriers, making use of only the magnetic images themselves and an assumption of approximately dipolar sources. If used on a large scale, the method provides the means to scan large areas of the rock sample, attaining potentially the number of magnetic moments necessary for paleomagnetic studies.

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